ACTUATOR USING A PIEZOELECTRIC ELEMENT

This application is based on Patent Application No. 11-360371 filed in Japan, the content of which is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to an actuator using a displacement element such as a piezoelectric element and the like.

Description of the Related Art

In the field of actuators using a displacement element such as a piezoelectric element, the object of improving drive efficiency has resulted in the proposal of actuators which drive a displacement element such as a single plate piezoelectric ceramic or the like to oscillate an elastic member at a resonance frequency, and actuators which drive a laminate-type displacement element formed of laminations of a plurality of piezoelectric ceramic thin plates itself at a resonance frequency.

When the former single plate displacement element is used, there is scant internal loss of the displacement element itself, since the drive force generated by the displacement element is transferred to the elastic member without attenuation. Accordingly, the drive efficiency is high. However, since the total surface area of the displacement element is small and the impedance is high, the drive voltage must be increased in order to increase the output. Particularly when used in a portable device, a several batteries must

be used, or a booster circuit must be used. For this reason such as solution is contrary to the demand for lower cost and more compact and lighter weight devices.

When the latter laminate-type displacement element is used, the total area of the displacement element is increased by the laminate plates, and impedance is reduced by the resonance, such that a large output can be obtained using a low drive voltage. However, there is a large internal loss due to use of electrodes and adhesive between each piezoelectric ceramic thin plate. Accordingly, there is an increased attenuation of the drive force generated by the displacement element, and relatively low drive efficiency. Furthermore, when used in portable devices, the battery consumption is comparatively rapid, necessitating frequent battery replacement.

OBJECTS AND SUMMARY

An object of the present invention is to provide an improved actuator.

Another object of the present invention is to provide an actuator using a low drive voltage and low power consumption.

A still further object of the present invention is to provide an actuator having a high drive efficiency.

These and other objects art attained by one aspect of the present invention providing a displacement element for generating a specific displacement by piezoelectric effect, a displacement expander for transmitting the displacement of the displacement element and expanding this displacement, a transmitter for transmitting the displacement expanded by the displacement

expander to a driven member, and a presser for pressing the transmitter against the driven member, wherein the oscillation of the displacement element is restrained by the oscillation of the displacement expander.

The spring constant of the displacement expander is desirably less than the spring constant of the displacement element.

It is further desirable that the displacement element is driven by a drive signal of a frequency near the simple natural frequency of the displacement expander.

It is still further desirable that the displacement element is a laminate-type piezoelectric element.

In this way the actuator of the present invention sets the phase of the electromotive force to the reverse of the phase of the drive signal by piezoelectric effect of the piezoelectric element, thereby making it possible to reduce the drive voltage.

The displacement of the displacement element can be expanded by the displacement expander by setting the spring constant of the displacement expander smaller than the spring constant of the displacement element, thereby making it possible to obtain a greater output with less power consumption.

The current flowing to the displacement element can be minimized by driving the displacement element by a drive frequency of a frequency near the simple natural frequency of the displacement element, thereby minimizing power consumption.

The displacement element formed as a laminate type piezoelectric element, thereby allowing reduction of the drive voltage of the displacement element.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects and features of the present invention will become apparent from the following description of the preferred embodiments thereof taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a schematic view showing the structure of a truss-type actuator;

FIG. 2 is a schematic view showing the structure of a laminate-type piezoelectric element used in the actuator;

FIG. 3 is a block diagram of a drive circuit of the actuator;

FIG. 4 illustrates the rotor rotation principle of the actuator;

FIG. 5 illustrates the voltage applied to two piezoelectric elements and the resulting displacements;

FIG. 6a is a schematic view of the displacement area comprising the piezoelectric element and elastic member in the actuator;

FIG. 6b is a schematic view showing the displacement area of FIG. 6a replacing an oscillation system using a spring and weight;

FIG. 7a illustrates the relationship between the frequency of the drive signal and the displacement of the piezoelectric element; and

FIG. 7b illustrates the relationship between the frequency of the drive signal and the displacement of the elastic member.

In the following description, like parts are designated by like reference numbers throughout the several drawings.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The embodiment of a truss-type actuator of the present invention is described hereinafter.

FIG. 1 shows the structure of a truss-type actuator. As shown in FIG. 1, the displacement element comprises metal elastic members 25 and 25' connected in series to a first piezoelectric element 10 and second piezoelectric element 10' so as to intersect at an approximate right angle. At the intersection end is adhered a tip member (displacement combining unit) 20 via adhesive. The base ends of the first piezoelectric element 10 and the second piezoelectric element 10' are respectively mounted to a base member 30 via bolts 23 and 23'.

The material of the tip 20 is desirably tungsten or the like having excellent wear resistance so as to obtain stability and high friction coefficient. The material of the base 30 is desirably stainless steel or the like having excellent strength and ease of manufacture. The material of the elastic members 25 and 25' is desirable aluminum, titanium, iron, copper, or alloys thereof. The adhesive is desirably an epoxy resin or the like having excellent strength and adhesion.

Details of the structure of the first piezoelectric element 10 and the second piezoelectric element 10' are shown in FIG. 2. In FIG. 2, the details are exaggerated in order to facilitate understanding of the structure. The laminate-type piezoelectric elements 10 and 10' are formed by alternating laminations of a plurality of ceramic thin plates 11 having piezoelectric characteristics such as PZT, and electrodes 12 and 13, and each ceramic thin plate 11 and electrodes 12 and 13 are fixed using an adhesive. The alternatingly arranged electrodes 12 and 13 are respectively connected to power source 16 and 16' via the signal leads 14 and 15. When a specific voltage is applied between

the signal leads 14 and 15, an electric field is generated in the lamination direction at the ceramic thin plates 11 interposed between the electrodes 12 and 13. Every second electric field is in the same direction. Accordingly, the ceramic thin plates 11 are laminated such that the polarization direction of every second layer is identical, i.e., adjacent ceramic thin plates 11 have opposite polarization directions. At the bilateral ends of the piezoelectric elements 10 and 10' is provided a protective layer 17.

When an alternating current drive voltage is applied between the electrodes 12 and 13 from the power sources 16 and 16', all ceramic thin plates 11 repeatedly expand and contract in the same direction, such that the entirety of each piezoelectric element 10 and 10' expands and contracts. In this actuator, the piezoelectric elements 10 and 10' are used as an oscillation source, and displacement is expanded by resonating the elastic members 25 and 25'.

The first and second piezoelectric elements 10 and 10' are driven by AC signals having a mutual phase difference, so as to move the tip 20 in an ellipse. When, for example, the tip 20 is presses against the cylindrical surface of a rotor 40 which is rotatable about a specific axis, the elliptical movement (including circular movement) of the tip 20 can be converted to a rotational movement of the rotor 40. Furthermore, when, for example, the tip 20 presses against the flat surface of a rod-like member (not illustrated), the elliptical movement of the tip 20 can be converted to linear movement of the rod member. Since the tip 20 presses against the rotor 40 or the like, a spring 41 is provided for contact to the base 30. The material of the rotor 40 is desirably a light weight metal such as aluminum or the like, and the

surface of the rotor 40 is desirably subjected to a an aluminum anodizing process to prevent wear through friction with the tip 20.

A block diagram of the drive circuit is shown in FIG. 3. An oscillator 50 oscillates a sinusoidal wave signal at a specific frequency. A phase controller 51 controls a delay circuit 52 in accordance with rotational speed, drive torque, rotation direction and the like targeting the rotor 40 as the driven member. In this way the delay circuit 52 generates a sinusoidal wave signal of shifted phase relative to the sinusoidal wave signal generated by the oscillator 50. A amplitude controller 53 controls a first amplifier 54 and a second amplifier 55, so as to mutually amplify the two sinusoidal wave signals of shifted phase. The sinusoidal wave signals amplified by the first amplifier 54 and the second amplifier 55 are respectively applied to the first piezoelectric element 10 and the second piezoelectric element 10'.

The principle of rotation of the rotor 40 by the truss-type actuator is described below. FIG. 4 shows the actuator of FIG. 1 pressed against the rotor 40 by a spring 41 at a specific pressure F. In FIG. 4, the symbol μ represents the friction coefficient. the voltages applied to the first piezoelectric element 10 and the second piezoelectric element 10', and the resultant displacements are shown in FIG. 5. When sinusoidal wave signals of different phase shown in FIG. 5 are applied to the first piezoelectric element 10 and the second piezoelectric element 10', respectively, the tip 20 connected to the first piezoelectric element 10 and the second piezoelectric element 10' moves in an elliptical movement or circular movement in conjunction therewith.

When this tip 20 is forced toward the cylindrical surface 40a of the rotor 40 at a specific pressure by the spring 41, the driven tip

20 describes an elliptical path or a circular path and intermittently contacts the cylindrical surface of the rotor 40. During this time the rotor 40 is driven in a specific direction together with the tip 20 by the friction force acting between the cylindrical surface 40a and the tip 20. The tip 20 is continuously driven via the repeated application of sinusoidal wave signals to the first piezoelectric element 10 and the second piezoelectric element 10', and intermittently drives the rotor 40 at small angle in a specific direction. As a result, the rotor 40 is driven in rotation about its rotational axis.

When two mutually intersecting and independent movements are combined, the intersection point describes a path in accordance with an elliptical movement method (Lissajous method). In the actuator of the present embodiment, various paths can be obtained by changing the phase difference and amplitude of the drive signals used to drive the first piezoelectric element 10 and the second piezoelectric element 10'. The rotational direction, rotational speed, rotational force (torque) and the like of the rotor 40 can be controlled by controlling the path of the tip 20. Specifically, the rotational speed is increased if the diameter of the path of the tip 20 is increased in a tangential direction relative to the rotation direction of the rotor 40. The rotational force is increased if the diameter f the path of the tip 20 is increased in a normal line direction relative to the rotor 40. Furthermore, if the phase is reversed, the rotational direction can be reversed.

FIGS. 6a and 6b are schematic drawings respectively showing the displacement unit comprising the first piezoelectric element 10 and the second piezoelectric element 10' substituted for

the displacement unit comprising an oscillation system of a spring and weight.

The mass of piezoelectric elements 10 and 10' and the elastic elements 25 and 25' are designated m1 and m2, the vertical oscillation spring constants are designated k1 and k2, the displacements from a standard length are designated X1 and X2, and the drive force (exciting force) generated by the piezoelectric elements 10 and 10' is designated F. The drive force when sinusoidal wave AC signals are applied to the piezoelectric elements 10 and 10' is drive force $F = F0\cos\omega t$.

When the internal resistance of the oscillation system shown in FIG. 6b is ignored, the displacements (amplitudes) X1 and X2 of the piezoelectric elements 10 and 10' and the elastic elements 25 and 25' are expressed below.

$$X1=F0\cdot(k2-m2\cdot\omega^2)/(m1\cdot m2\cdot\omega^4-(m1\cdot k2+m2\cdot(k1+k2))\omega^2+k1\cdot k2) \quad (1)$$

$$X2=F0\cdot k2/(m1\cdot m2\cdot\omega^4-(m1\cdot k2+m2\cdot(k1+k2))\cdot\omega^2+k1\cdot k2) \quad (2)$$

The relationship between the frequency of the drive signal and the displacement (amplitude) X1 and X2 are shown in FIGS. 7a and 7b. As can be understood from FIG. 7a, at a specific frequency f $(f=k2/m2)^{1/2}$, the displacement X1 of the piezoelectric elements 10 and 10' becomes zero [0]. In the present embodiment, the frequency f at which the displacement X1 of the piezoelectric elements 10 and 10' becomes zero is used to drive the piezoelectric elements 10 and 10'. In equation (1) above, the condition under which the displacement X1 of the piezoelectric elements 10 and 10' becomes zero is stated below.

$$k2-m2\cdot\omega^2=0,\ \text{where}\ \omega^2=k2/m2 \qquad (3)$$

Each frequency satisfying this condition is equal to the simple natural frequency of the elastic members 25 and 25'. When the value ω satisfying equation (3) is substituted in equation (2), the following is obtained.

$$X2=F0\cdot k2/(m1\cdot k2^2/m2-m1\cdot k2^2/m2-(k1+k2)\cdot k2+k1+k2)=-F0/k2 \qquad (4)$$

The displacement X2 of the elastic members 25 and 25' are equal to the extension from equation (4) when the drive force of the piezoelectric elements 10 and 10' are statically added to the elastic members 25 and 25'.

The negative sign on the displacement X2 (=F0/k2) of the elastic members 25 and 25' reflects that the phase of the elastic members 25 and 25' are the opposite phase of the drive force (exciting force) of the piezoelectric elements 10 and 10'. That is, the oscillation of the elastic members 25 and 25' nullify the oscillation of the piezoelectric elements 10 and 10'.

When the extension of the piezoelectric elements 10 and 10' with a static electric field applied is designated X0, F0=K1·X0, such that the following equation (5) is derived.

$$X2=-X0\cdot k1/k2 \qquad (5)$$

The displacement of the elastic members 25 and 25' can be expanded more than the displacement of the static displacement of the piezoelectric elements 10 and 10' by making the spring constant

$k2$ of the elastic members 25 and 25' smaller than the spring constant $k1$ of the piezoelectric elements 10 and 10' ($k1>k2>1$).

The spring constant k of a member formed of a homogenous material can be represented by $K=SE/L$ when the member cross section is designated S, length is designated L, and coefficient of elasticity is designated E. Accordingly, the spring constants $k1$ and $k2$ of the piezoelectric elements 10 and 10' and the elastic members 25 and 25' can be controlled by design, and the displacement $X2$ of the elastic members 25 and 25' can be expanded by satisfying the relationship $k1>k2>1$.

As described above, when the piezoelectric elements resonate, impedance decreases and the current flow to the piezoelectric elements increases. Consider that this current increase mechanically oscillates the piezoelectric elements which generates electromotive force by the voltage effect on the piezoelectric element itself, and the current flows readily by matching the phase of the electromotive force and the phase of the drive signal. In the present embodiment, this phenomenon is used in reverse, by suppressing the mechanical oscillation of the piezoelectric element to reverse the phase of the electromotive force produced by the voltage effect to the opposite of the phase of the drive signal, to reduce the drive current (theoretically to zero [0]). Actually, although the conditions of internal resistance differ for the piezoelectric elements 10 and 10' and the elastic members 25 and 25', the displacement $X1$ of the piezoelectric elements 10 and 10' can be nullified by a frequency near the simple natural frequency of the elastic members 25 and 25', thereby minimizing the current of the drive signal. As a result, as an actuator, the a specific displacement amount (output) is assured, and

the power consumption necessary for actuation can be reduced. Furthermore, since a laminate-type piezoelectric element is used as a displacement element, the drive voltage can be reduced.

Although displacement units comprising two groups of piezoelectric elements 10 and 10' and elastic members 25 and 25' for driving a tip 20 are arranged so as to intersect in the above described embodiment, the present invention is not limited to this arrangement inasmuch as other optional angles, such as, for example, 45°, 135° and the like also may be used. The number of displacement units is not limited to two, and groups of three or more displacement units may be used, so as to drive the displacement elements with three or four degrees of freedom. The actuator of the present invention is not limited to truss-type actuators, and may be an actuator such as a toric-type, π-type, impact-type and the like, and may be applied to general actuators of types which excite an elastic member by oscillation of a piezoelectric element.

Although the present invention has been fully described by way of examples with reference to the accompanying drawings, it is to be noted that various changes and modifications are apparent to those skilled in the art. Therefore, unless such changes and modifications depart from the scope of the present invention, they are to be construes as being included therein.